METHOD AND APPARATUS FOR REDUCING
THE PARACHUTING OF A PROBE

BACKGROUND OF THE INVENTION

1.   Field of Invention

The present invention is directed to scanning probe microscopy. More particularly,

the present invention is directed to a method and apparatus for reducing the parachuting of

5   a probe used in an atomic force microscope.

2.   Description of Related Art

Scanning probe microscopes are used to make extremely high resolution

measurements. An oscillating cantilever or probe is used to scan a sample surface and

obtain information representative of the surface. Activity of the probe responsive to surface

10   variations is monitored by a detection system. The detection system is typically an optical

beam system. The height of the probe relative to the sample surface is then adjusted to

maintain constant one or more probe operational parameters based on the monitored

activity. Piezoelectric positioners are often used to adjust the height of the probe relative to

the sample surface. Correlation of the adjustment amount in the Z direction versus the

15   position of the probe along the surface in the X and Y directions is used to create a map of

the surface.

Unfortunately, as the probe traverses the surface of the sample, the probe may not

accurately follow the surface, particularly at abrupt drop-offs or ledges in the surface

where the probe will tend to depart from and "parachute" over some portion of the surface.

20   For example, when the probe reaches a drop off in the surface, the probe will only

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gradually lower itself again to the surface (the bottom of the drop-off) as the probe continues its scan, instead of immediately dropping to the surface below the ledge. This parachuting effect causes abrupt vertical drops that actually exist in the surface to be erroneously represented as gradual surface changes.

5   In particular, in current configurations of Tapping™ AFM scanning probe control, a probe is set to tap the surface at a constant oscillating amplitude. The change in the probe tapping amplitude, or other probe operational parameter, is used as a feedback error signal. As the cantilever probe traverses off an abrupt ledge or edge of a plateau, the cantilever leaves the surface, i.e., parachutes. Accordingly, the probe's oscillation amplitude will

10   grow until the error is sufficiently large to cause a vertical ("Z") motion piezo to respond and lower the cantilever towards the surface, reestablishing the pre-set amplitude, or other operational parameter. The duration of amplitude growth, and therefore error generation, can be quite long such that while the probe remains off the surface, surface features are passed by and not measured. To compensate for prolonged and slow error generation, and

15   in an attempt to lower the probe to the surface more quickly so that surface features are not missed, the gain of the feedback error signal can be increased but this causes the tip to tap hard on the surface. Such hard tapping reduces error growth time and shortens the free parachuting state of the cantilever but causes other problems. Hard tapping causes the tip to impact the surface with great force which quickly results in damage to the tip and/or

20   sample. Hard tapping is particularly damaging if the tip runs into an upward sloping feature where the probe slams into the surface and damages the tip and/or sample. Finally, these problems are exacerbated as scan rates increase.

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SUMMARY OF THE INVENTION

The present invention provides a method and apparatus for reducing the parachuting of a probe in an atomic force microscope. The apparatus includes an oscillating probe, a phase detection circuit coupled to the oscillating probe, and a probe drive boosting circuit

5   coupled to the phase detection circuit and the probe. The phase detection circuit detects the phase signal corresponding to parachuting of the probe, and the probe drive boosting circuit boosts a signal to the probe based on the phase signal detected by the phase detection circuit to produce a boosted probe drive signal.

The phase detection circuit includes a precision full wave rectifier and an envelope

10   detector coupled to the precision full wave rectifier, wherein the precision full wave rectifier rectifies a phase signal of the probe to produce a rectified phase signal and the envelope detector detects the rectified phase signal to produce an envelope detected signal. The phase detection circuit further includes a comparator coupled to the envelope detector, and an event detector and hold off circuit coupled to the comparator, wherein the

15   comparator and the event detector and hold off circuit generate an event signal from the envelope detected signal. The phase detection circuit further includes a multiplier coupled to the event detector and hold off circuit, wherein the multiplier combines the event signal with a probe drive signal to produce the boosted probe drive signal.

The apparatus further includes an event level setting circuit coupled between the

20   event detector and hold off circuit and the multiplier, wherein the event level setting circuit sets an event level of the event signal. The boosted probe drive signal is boosted to a level 20 to 30 percent higher than the probe drive signal. This higher level is adjustable. The

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event detector and hold off circuit delays generation of the event signal for a predetermined time.

The method includes scanning the surface of the sample with an oscillating probe, detecting a reduction of a variation of a phase signal of the probe indicative of free

5   oscillation of the probe, and increasing a rate of the probe response to steep variations of sample surface features.

The detecting step further includes rectifying the phase signal of the probe to produce a rectified phase signal, and envelope detecting the rectified phase signal of the probe to produce an envelope of the detected phase signal of the probe. The increasing step

10   further includes boosting a drive signal of the probe to produce a boosted drive signal of the probe in the event of parachuting. The detecting step also further includes triggering an event signal based on the detected phase signal, and the boosting step further comprises boosting the drive signal of the probe by combining the event signal with the drive signal of the probe to produce a boosted drive amplitude signal. The boosted drive signal is 20 to 30

15   percent of the drive signal above the drive signal.

The present invention locates the parachuting (free oscillation) event by using phase criteria and boosts the probe drive signal to expedite error generation. Since the probe drive signal is only boosted during the parachuting event, the tip is able to continue to tap lightly without sacrificing scanning speed. Consequently, probe parachuting is reduced or

20   eliminated without causing hard tapping and thus without damaging the tip and/or sample.

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BRIEF DESCRIPTION OF THE DRAWINGS

The preferred embodiments of the present invention will be described with reference to the following figures, wherein like numerals designate like elements, and wherein:

Fig. 1 is an exemplary block diagram of a paraboost system for reducing the parachuting of a probe;

Fig. 2 is an exemplary block diagram of a paraboost module according a preferred embodiment;

Figs. 3 is an exemplary illustration of probe operation without a paraboost module;

Fig. 4 is an exemplary illustration of probe operation with a paraboost module;

Fig. 5 is an exemplary block diagram of the paraboost module according to a preferred embodiment;

Figs. 6-10 are exemplary illustrations of a phase signal at stages a-g of the paraboost module;

Fig. 11 is an exemplary illustration of resulting signals of a probe system without a paraboost module;

Fig. 12 is an exemplary illustration of resulting signals of a probe system when the paraboost module is used; and

Fig. 13 is an exemplary flowchart of the operation of the paraboost system.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

When a scanning probe of a Tapping™ AFM taps the surface of a sample there are several operational parameters of the probe that can be detected and used to measure

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surface properties. One such operational parameter is the oscillation amplitude of the tapping cantilever. Another operational parameter is the phase difference between a sinusoidal drive signal and a cantilever response signal. When the cantilever is oscillating freely in air ("free oscillation"), the phase is approximately 90 degrees. When the probe is

5   tapping the surface, the phase varies significantly. The deviation of the tapping phase from the free oscillation phase is normally a few tens of degrees with the sign depending on repulsive or attractive tip/surface interaction. As a result, the free oscillating state of the cantilever is uniquely defined as the state which holds a 90 degree phase. In the figures provided, the phase is plotted with a 90 degree offset so that free oscillation appears at zero

10   degrees.

Fig. 1 is an exemplary block diagram of a paraboost system 100 for reducing the parachuting of a probe. The paraboost system 100 includes a paraboost module 110, a probe 120 including a cantilever and a tip, an oscillator 130, a Z-module 140, a control module 150, a sample 160, and a surface 170. The Z-module 140 is a mechanism which

15   causes the probe to approach and separate from the surface 170, such as a Z-axis piezoelectric element that changes a distance between the probe 120 and the surface 170. The Z-module adjusts either the distance of the probe relative to the surface or the surface relative to the probe. The oscillator 130 preferably oscillates the probe 120 so as to intermittently contact the surface 170 in accordance with this assignee's Tapping™ AFM to

20   map the surface 170.

In overview, the paraboost module 110 detects operation of the probe 120, including parachuting of the probe 120 and boosts an error signal sent to the control

module 150. The control module 150 controls movement and location of the probe 120

with respect to the surface 170. In particular, the control module 150 controls the distance

between the probe 120 and the surface 170 based on detected operational parameters of the

probe. The control module 150 may include an additional signal processor which operates

5   in response to error signals from the paraboost module 110. For example, the control

module 150 may integrate an error signal from the paraboost module 110 caused by under

or over oscillation of the probe 120. The control module 150 then adjusts the distance

between the probe 120 and the surface 170 to compensate for the error signals. For

example, the control module 150 lowers the probe 120 if the paraboost module 110 or

10   another sensor detects that the probe 120 is too far from the surface 170.

In a preferred embodiment, the probe 120 oscillates and taps the surface 170 at a

predetermined set point amplitude. The probe also has a free amplitude oscillation when it

is away from the surface 170 (i.e., oscillating in air). The set point amplitude of oscillation

of the probe 120 when it taps the surface 170 is usually 70%–90% of the free oscillation

15   amplitude. To obtain an accurate map of the surface 170, it is desired to keep the tapping

amplitude of oscillation constant as the probe scans the surface, i.e., to return it to the set

point oscillation amplitude if it strays. Accordingly, when an operational parameter of the

probe 120, such as amplitude of oscillation changes (e.g., decreases) indicating that the

probe is too close to the surface 170, the Z-module 140 retracts the probe 120 from the

20   surface 170 until the probe again oscillates at its set point. Likewise, when the amplitude of

oscillation of the probe 120 increases above the set point, indicating that the probe 120 is

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too far from the surface, the Z-module 140 lowers the probe 120 towards the surface 170

to again reestablish the amplitude of oscillation at the set point.

In controlling the Z-module, the paraboost module 110 detects oscillation

amplitude, phase, and/or other properties of the probe 120. These properties are detected,

5 for example, by any number of standard detector schemes, such as a laser reflecting off the

back side of the cantilever and onto a bi-cell or quad detector. An error signal from the

detector is sent to the control module 150. If the oscillation amplitude of the probe 120 is

too high, for example, the non-zero error signal is integrated and accumulated by the

control module 150. When enough error signal is integrated, the control module 150

10 commands the Z-module 140 to lower the probe 120 towards the surface 170. The error is

integrated so that abrupt changes are not detected too quickly, which may cause the Z-

module 140 to engage in unwanted oscillation. If the probe 120 encounters a deep recess

175 in the surface 170, it is desirable to lower the probe 120 to the bottom of the recess

175 as quickly as possible. In conventional devices, this is accomplished by increasing the

15 gain of the error signal. Unfortunately, high gain makes the system susceptible to

instability of the Z-module. In the present invention, however, no such Z module instability

occurs when the probe is lowered quickly because instead of increasing gain of the error

signal, probe oscillation is increased by boosting the probe drive signal. This causes the

error signal to accumulate more rapidly in the control module 150 which causes the Z-

20 module 140 to lower the probe 120 more rapidly. Therefore, the Z-module 140 responds to

and reduces parachuting of the probe 120 without causing the probe to oscillate or become

unstable.

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According to a preferred embodiment, the paraboost module 110 detects parachuting of the probe 120 by detecting properties of the phase of the probe 120. In particular, the present invention takes advantage of the fact that the phase of the probe oscillation is distinctly different when the probe 120 is tapping surface 170 than when it begins to freely oscillate. During tapping the phase is "noisy," while during free oscillation the phase quiets. Therefore, parachuting can be detected when the phase of the probe 120 becomes quiet.

Fig. 2 is an exemplary block diagram of a paraboost module 110 according to a preferred embodiment. The paraboost module 110 includes a detector module 210 and a boost module 220. In operation, the detector module 210 detects the phase of the oscillating probe 120. When the detector module 210 detects the reduction of a variation of the phase signal from the probe 120, the detector module 210 instructs the boost module 220 to increase the oscillator 130 drive signal supplied to the control module 150 to increase the amplitude of the oscillating probe 120. By boosting the drive to the oscillating probe 120, the vibration amplitude of the cantilever 120 is increased, the error signal is increased, and the control module 150 integrates the error more quickly. Accordingly, the Z-module 140 is instructed to lower the probe 120 towards the surface 170 faster.

Figs. 3 and 4 are exemplary illustrations of the desirable effects of the paraboost module 110. Fig. 3 illustrates a probe 120 scanning a surface 170 from left to right without using the paraboost module 110. As illustrated, when the probe 120 reaches an edge of the surface 170, the probe 120 gradually lowers along the dotted line to the bottom of the surface 170. Therefore, the edge of the surface 170 is not properly detected and mapped.

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Fig. 4 illustrates the scanning of a surface 170 with the probe 120 from left to right using the paraboost module 110. As illustrated, the probe 120 quickly reacts to the edge of the surface 170.

Fig. 5 is an exemplary block diagram of the paraboost module 110 according to a

5   preferred embodiment. The paraboost module 110 includes a differential amplifier 510, a precision full-wave rectifier 520, a clamp and gain circuit 530, an envelope detector 540, a comparator with hysteresis circuit 550, an event detector and hold off circuit 560, a correction period and reset event detector circuit 570, an event level setting circuit 580, and an analog multiplier 590. Figs. 6–10 are exemplary illustrations of a phase signal at

10   stages a–g of the paraboost module 110.

In operation, the paraboost module 110 detects parachuting of the probe 120 based on the probe phase signal when the phase signal quiets as illustrated in Fig. 6, waveform (a). In particular, the phase signal waveform (a) enters the paraboost module 110 through the differential amplifier 110 at location (a). The differential amplifier 510 is useful to

15   reduce noise of the signal when the paraboost module 110 is relatively far from the sensors detecting the phase of the probe 120. The amplified phase signal then enters a precision full-wave rectifier 520 and then is rectified to produce full-wave rectified waveform (b). Waveform (b) then enters a clamp and gain circuit 530 and proceeds through an envelope detector 540 which converts the ragged edges into perimeter edges to produce the envelope

20   detected waveform (c) illustrated in Fig. 7.

The event detector and hold off circuitry 560 prevents false triggering. In other words, the event detector and hold off circuitry 560 waits a set amount of time before

signaling a no-phase condition. For example, the event detector and hold-off circuitry 560

can ignore events less than 1 ms in duration for cantilevers with 100kHz resonance

frequency and Q 100. The holding time can be shorter if the cantilever resonance frequency

is higher. The waveform (c) then enters the comparator with hysteresis 550 and proceeds

5   through the event detector and hold off circuitry 560 to produce waveform (d).

Waveform (d) then enters correction period with reset event detector circuitry 570

to produce waveform (e). As illustrated in Fig. 8, and discussed above, the event detector

and hold off circuitry 560 and the correction period and reset event detector circuitry 570

ignores false events, such as those that are less than one millisecond. Accordingly, only

10   events that are greater than one millisecond are detected and output as a dashed line

waveform (e). Waveform (e) then enters event level setting circuitry to adjust the pulse of

the waveform (e) to the desired level by using a level setting input and to produce

waveform (f) as illustrated in Fig. 9. Waveform (f) then proceeds through an analog

multiplier 590 where it is combined with the cantilever drive signal to boost the drive

15   amplitude resulting in waveform (g) as illustrated in Fig. 10. Boosted drive amplitude

waveform (g) is then used to drive the probe 120.

Fig. 11 is an exemplary illustration of resulting signals of a probe system without a

paraboost module. The signals include a detected map signal 1110 of the surface 170 using

a probe 120 scanning from right to left, a phase signal 1120 of the probe 120, and an

20   amplitude of a drive signal 1130 to the probe 120. Fig. 11 shows how the probe begins

parachuting in map signal 1110 at point 1115 when the phase signal 1120 is level (quiet) at

point 1125, without using the paraboost module 110. Thus, without the use of paraboost

module 110 the amplitude of the drive signal 1130 is not boosted to compensate for the parachuting.

Fig. 12 is an exemplary illustration of resulting signals when the paraboost module 110 is used and other experiment of conditions are identical to those in Fig. 11. The signals

5   include the mapped surface signal 1210, the phase signal 1220, and the amplitude of the drive signal 1230. As illustrated, when the paraboost module 110 detects a leveling of the phase signal 1220 at point 1225 indicating an abrupt drop in the surface 170 at point 1215, the amplitude of the drive signal 1230 is adjusted at point 1235. In particular, the leveling of the phase signal is a reduction of the variation of a phase signal from the probe 120.

10   Thus, the leveling is a quieting of the phase signal from the probe 120. Therefore, the paraboost module boosts the cantilever drive signal, the control module 150 integrates the error more rapidly and the Z-module 140 lowers the probe 120 faster. Accordingly, as shown in signal 1210, an abrupt variation in the surface 170 is more accurately detected.

Fig. 13 is an exemplary flowchart of the operation of the paraboost system 100. The

15   flowchart begins at step 1310. In step 1320, the probe 120 scans across the surface 170. In step 1330, the paraboost system 100 detects the phase signal of the probe 120. In step 1340, the paraboost system 100 boosts the drive signal of the probe 120. In step 1350, the paraboost system 100 adjusts the distance between the probe 120 and the surface 170. For example, the paraboost system 100 reduces the distance between the probe 120 and the

20   surface 170 when the paraboost system 100 detects free oscillation of the probe 120. In particular, when free oscillation is detected, the paraboost system increases an error signal which in turn increases a drive signal of the Z-module 140 to reduce the distance between

the probe 120 and the surface 170. For example, the error signal or the drive signal are boosted 20–30 percent.

While this invention has been described with specific embodiments thereof, it is evident that many alternatives, modifications, and variations will be apparent to those

5   skilled in the art. Accordingly, the preferred embodiments of the invention as set forth herein are intended to be illustrative, not limiting. Various changes may be made without departing from the spirit and scope of the invention.